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NON-NEWTONIAN FLOW FOR HUMAN IMPACT PROTECTION

FINAL REPORT

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Abstract : The impact absorbing properties of starch/brine dilatant suspensions were characterized with an instrumented, pendulum-type impact tester. The starch concentrations were varied between 47.5 and 52.5% and sealed in heavy rubber bags of varying thickness. The temperature of the filled rubber bags was varied between 45 and 110F. Impacting energies ranged between 30 and 141 ft-lbs with velocities of 11 and 17 ft/sec. The dilatant suspensions were found to be highly efficient and reusable energy absorbers under all test conditions. Impactor penetration, peak deceleration, and jerk varied depending on the impact energy input, impact velocity, bag wall thickness, and, to a lesser extent, starch concentration and temperature. The filled bags readily conform to the shape of a 1 cm radius impactor and yield relatively low peak deceleration and jerk. There was no noticeable deterioration of the dilatant properties as a result of temperature cycling and repeated impacts. (Author)

Descriptors : (*AIRCRAFT SEATS, SHOCK RESISTANCE), (*COLLOIDS, SHOCK RESISTANCE), (*SHOCK ABSORBERS, COLLOIDS), IMPACT SHOCK, IMPACT TESTS, MATERIALS, ABSORPTION, ACCELERATION, EJECTION SEATS

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The energy absorption characteristics of a number of dilatant suspension systems were evaluated using a modified pendulum impact tester. Two systems which were found to have superior impact energy absorption properties are 50% corn starch + 2% SPAN 20 in a concentrated (26.5%) NaCl solution and 70.5% glass microbeads (29μ) in water. The impact properties of all the dilatant systems were found to be significantly better than currently available ejection seat cushion materials. A qualitative correlation between the impact parameters measured in this investigation and the forces experienced during simulated ejection tests was made.

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1. INTRODUCTION

As modern technology continues to develop, ever increasing demands are imposed on the human body. Situations often arise during which the body must withstand large impacts. Due to difficulties in developing realistic models of the body detailed information about the forces which are most damaging during impacts is not available. Some of the most important parameters are the energy absorbed, the peak force generated, the rise time of the force (jerk), the duration of the force application, and to a lesser extent the change in momentum or impulse[(1-4)]. The development of energy absorbing materials to lessen these effects is vitally needed.

Initial approaches to this problem produced rather limited success. These were elastic foam rubber cushions and crushable polystyrene and polyurethane foams. Recent developments include crushable expanded metal components, such as those used in collapsible auto steering wheel columns, and hydraulic damping by fluid flow eg. the water filled auto bumpers.

The use of fluid flow in energy absorption is very promising because of its versatility. By varying the parameters which control the flow (the size and number of the geometrical orifices, the viscosity of the fluid etc.) a wide range of energy absorption characteristics can be obtained and tailored to meet specific service requirements. To date the fluids employed in these applications have been Newtonian fluids. These fluids have constant viscosity and their flow rates must be controlled by changing the external variables. Much more versatility is possible if non-Newtonian fluids are used. The viscosity of these fluids is dependent on the shear rate. Two examples are pseudoplastic fluids and dilatant fluids[(5)]. The viscosity of pseudoplastic fluids decreases as the shear rate increases. A common use for these fluids is in lubricating greases or shear thinning (dripless) paints. If the decrease in viscosity is

time dependent the fluids are called thixotropic. Dilatant fluids become more viscous as the shear rate increases. These fluids are usually composed of concentrated slurries of solid particles suspended in a low viscosity liquid. Wet beach sand is the classical example. The tendency of these dilatant fluids to become stiffer upon sudden shearing makes them uniquely applicable as impact energy absorbing materials.

Initial research in the use of dilatants for this purpose was conducted at the Franklin Institute Research Laboratories. The program[6] was specifically designed to develop dilatant suspensions for use as aircraft ejection seat cushions. The dilatant fluids are particularly suited to this application since they provide a compliant, comfortable cushion under the low applied shear rates of normal flight and yet exhibit a very high viscosity during ejection. The ejection process produces acceleration pulses of 15-19 g's on the seat pan below the cushion. Compliant cushions are compressed beneath the pilot during the initial stages of ejection giving him a velocity much lower than the seat below. When the cushion "bottoms" the firm contact amplifies the acceleration and the pilot may experience forces in excess of 35 g's.

In the first FIRL program the system chosen for study was suspensions of cornstarch in concentrated salt solution. This system was chosen because of its availability and relative ease of handling. The salt solution was used to suppress the biological decay of the starch. Testing was conducted using a pendulum impact tester which was modified specifically to characterize impact absorbing materials. Key parameters measured were the deceleration of the impactor and its penetration into and rebound out of the cushions. The results of the program indicated that a dilatant suspension is a very efficient impact energy absorber. Three inch thick cushions were found to be quite sufficient to stop the impactor even at the highest energy tested (140 foot pounds). More importantly, very little rebound occurred i.e. almost 100% of the initial energy was absorbed. By comparison, foam materials absorbed only 50 to 90% of the initial energy. Excessive elastic rebound in the cushion

of an ejection seat system would cause elastic energy to be accumulated during initial stages of the ejection. The release of this energy at a later stage would undoubtedly amplify the peak force experienced by the man.

The purpose of the present program was to characterize impact absorption properties for a range of dilatant suspensions and to compare them to currently available ejection seat cushion materials. An attempt was also made to correlate, as quantitatively as possible, the results of the impact tests with data from actual ejection tests.

2. PROCEDURES

2.1 Instrumentation

The experimental apparatus and instrumentation were discussed in detail previously[6]. The dilatant suspensions were contained in rubber bags and impacted using a modified Wiedemann-Baldwin Model SI-I Impact Tester. The deceleration of the impacter was measured with an Endevco Model 2225 piezoelectric accelerometer which was mounted on the pendulum bob. The output signal from the accelerometer was fed to a Kistler Model 503 charge amplifier and then to one channel of a Tektronix 454/R454 oscilloscope for viewing and recording. The depth of penetration into the test specimen and the rebound after the impact was measured using a precision wire wound potentiometer (Helipot Model S1277, 10K) mounted on the pivotal axis of the pendulum. The potentiometer was wired to the second channel of the Tektronix oscilloscope for the penetration measurements and to a Sanborn chart recorder for the rebound measurements.

2.2 Test Parameters

The impact velocity and energy were varied by changing the weight of the pendulum bob and the height from which it was dropped. Impact energies used were 33.61, 58.77, 80.63 and 140.98 foot pounds. The first two energies correspond to a velocity of 11.0 and the last two to a velocity of 17.0 feet per second.

The raw data from each test consists of a dual trace oscillograph showing deceleration and depth-of-penetration as a function of time, and a strip chart showing the maximum angle of rebound of the pendulum. From this unprocessed data, the values of a number of important variables can be determined. These are discussed below.

2.2.1 ABSORBED ENERGY

The amount of the initial impact energy that is absorbed by

the specimen is determined by the angle of rebound of the pendulum. If all the available energy were absorbed there would be no rebound. In practice all specimens showed at least some rebound. The rebound energy is

$$E_R = LW(1-\cos\Theta)$$

where E_R = rebound energy (ft·lbs)

L = length of the pendulum arm, ft.

W = weight of the pendulum bob, lb

Θ = the angle of rebound (degrees)

The absorbed energy is then simply

$$E_A = E_I - E_R$$

where E_I = the initial impact energy (ft·lbs)

and E_A = the absorbed energy (ft·lbs)

The values of absorbed energy are reported in percentages as the energy absorption efficiency.

2.2.2 DEPTH OF PENETRATION

The distance which the face of pendulum bob travels into a test specimen before it stops and begins its outward rebound is known as the depth of penetration. It is measured as shown in Figure 2 by extending a vertical line down from the initial impact point of the deceleration trace across the penetration trace. (The initial impact point is easily recognized by the abrupt discontinuity near the start of the deceleration trace.) This intersection gives the initial contact point of the pendulum face with the rubber bag. From the initial contact point to the maximum

penetration point (lowermost excursion of penetration trace) the depth of penetration is measured graphically.

Studies of human impact[7-9] have indicated that the body is sensitive to at least three characteristics of the acceleration-time cycle to which it is subjected; these characteristics are peak force (deceleration), dwell time or period of force application, and the initial rise time of the force.

2.2.3 PEAK DECELERATION

The most obvious of the three parameters is the peak or maximum deceleration. Figure 1 is a typical example of an oscillograph of deceleration (and penetration) as recorded from the impacting of a dilatant suspension-filled rubber bag. Figure 2 is a graphic key to the interpretation of the oscillographs. It should be noted that peak deceleration is simply the maximum vertical excursion of the deceleration trace from the base or zero line. It is measured with a pair of draftman's dividers. Each vertical division (the grid lines) represents 20 g's.

2.2.4 DWELL TIME

The dwell time is a measure of the duration of force application and is measured as shown in Figure 2. After the value of the peak deceleration is determined a horizontal line representing half this value is drawn across the deceleration trace as shown. Dwell time is the distance (time) between intersections.

2.2.5 JERK

Jerk is defined as the rate of change of acceleration or deceleration with respect to time. The units are g/unit time and in this study they are g/millisecond. The value of jerk is determined by measuring the slope of deceleration trace at the desired point. For this study the maximum jerk was determined for both the deceleration and the portions

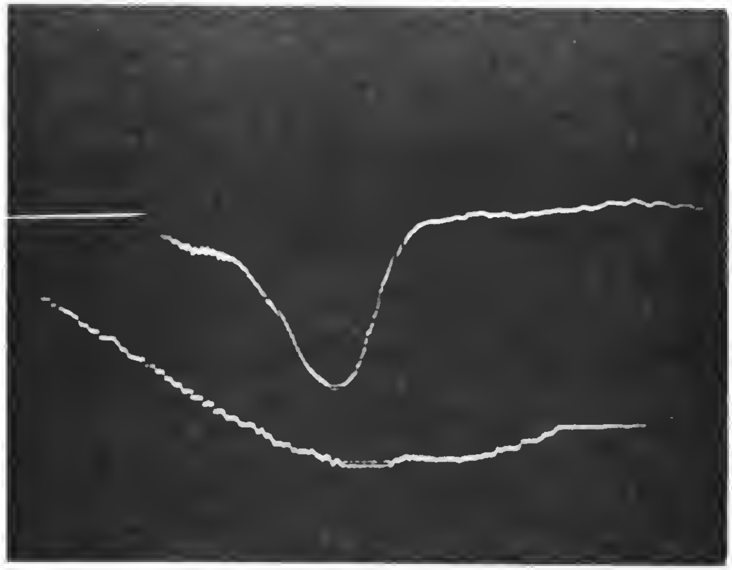


Fig. 1. Typical Oscillograph of Deceleration and Penetration of Impacting Pendulum Bob

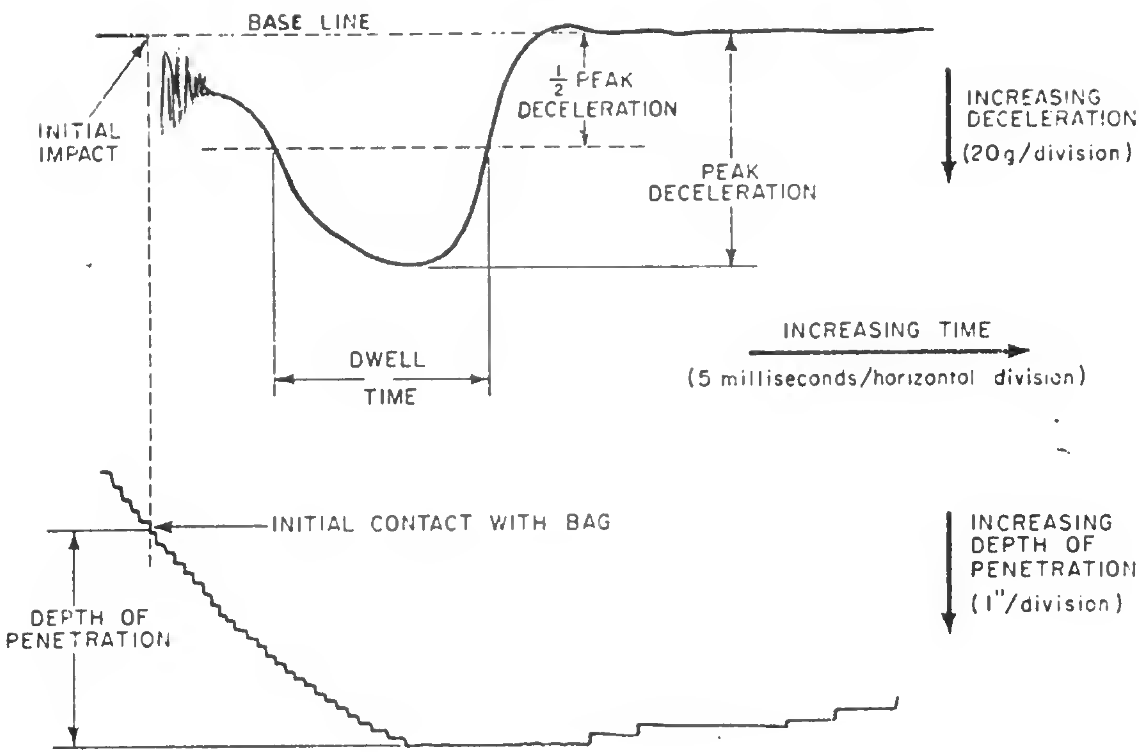


Fig. 2. Interpretation of Impact Oscillograph

of the trace rebound. In the first case the pendulum face is being slowed down or decelerated at an increasing rate by the action of the test specimen; thus, the jerk determined on that portion of the trace is called the initial jerk. In the second case the pendulum has been brought to a halt and is beginning to rebound and the "jerk" measured on this portion of the trace is called the rebound jerk. There is very little rebound in the case of the dilatant test specimens used in this study thus, the deceleration peak decays rapidly to zero. From a practical standpoint the initial jerk is a measure of the rise time of the force.

From the standpoint of bodily injury during impact the most important of these parameters is the peak deceleration. The jerk is not considered a critical measure of potential injury but since it describes the shape of the deceleration time curves it is very useful in characterizing the properties of the various dilatant suspensions. The energy absorption efficiency is indirectly very important from the standpoint of injuries because excessive elastic rebound of a seat cushion can result in a sizeable amplification of the peak forces experienced during an actual ejection.

It is important to note that these variables are not independent and thus are influenced by one another. For example, the deceleration is simply the rate of change of velocity of the impactor. Therefore a lower peak deceleration means a longer time expired before the impactor is stopped. This will generally produce a larger depth of penetration.

2.3 Test Specimens

The primary experimental variable in the investigation was the composition of the dilatant suspensions. An attempt was made to characterize a wide range of dilatant fluids. The general experimental procedure was to prepare a suspension and qualitatively test it for dilatant properties. If a definite dilatancy occurred the suspension was then impacted.

During impacting the specimens were contained in Tillotson #30 (40 oz.) rubber balloons, 0.020 in. wall. The filled rubber balloons or bags were sealed so that air was excluded. Each filled bag weighed about 3 lbs. and had a thickness of 3-1/4" along the impact axis.

Except for tests in which the effect of settling was to be studied the bags were always kneaded before impacting. Each test suspension was impacted three times at each of the four energy levels tested above. Reproduceability was very good and the data presented is an average of the three tests. All experiments were run at room temperature.

3. RESULTS AND DISCUSSION

The experiments in the present investigation were conducted with three main objectives. 1) To characterize the properties of various dilatant suspensions with the goal of developing the technology to accurately control the properties of the suspensions to meet specific service requirements. 2) To compare the properties of the dilatant suspensions to currently used impact absorbing materials, specifically airplane ejection seat cushion materials. 3) To compare, to the extent that data becomes available, the impact parameters measured in the FIRL tests with the forces experienced during simulated ejection tests.

3.1 Characterization of the Properties of Dilatant Suspensions

Since the starch-brine system was previously found to have outstanding impact properties it was used as a standard for testing in the present program. It consists of Globe Cornstarch #3005 suspended in a concentrated (26.5%)* aqueous sodium chloride solution. The starch concentration is 50%. The impact properties of this suspension are given in Table 1.

Dilatant suspensions[5,7,8] are usually composed of fine solid particles dispersed in high concentration in a fluid medium. At low rates of applied loading the suspension flows freely with a low apparent viscosity but above some critical flow rate the resistance to flow increases markedly. Flow dilatancy is believed to occur when the imposed shear rate becomes so high that the steady state distribution of particles is seriously disturbed. This results in increased contact forces between the particles and consequent breakdown of the lubricating film between them. The particles then begin to come into direct contact and the resistance to flow increases sharply. Thus any change in a system that affects the distribution or lubrication of the particles should affect

*All percentages are weight percent unless specified otherwise.

Initial Impact Energy E_I(ft·lbs)	Impact Velocity V(ft/sec)	Energy Absorption Efficiency, E_{abs} (percent)	Penetration (inches)	Dwell Time (milliseconds)	Peak Deceleration (g)	Maximum Jerk (g/millisecond)	
						Initial	Rebound
33.61	11.0	96.5	1.38	8.00	47.8	11.4	12.9
			ΔP .15				
58.77	11.0	95.4	1.53	8.30	45.7	10.6	11.3
			ΔP .24				
80.63	17.0	96.8	1.77	5.36	91.3	13.1	31.6
			ΔP .07				
140.98	17.0	97.3	1.84	7.30	83.7	15.6	31.6

TABLE 1: Impact Properties of the Standard Starch-Brine Dilatant Suspension

the dilatant properties. Two basic approaches were used in characterizing the dilatant systems. The first was to evaluate alterations of the standard starch suspension and the second was to test various other promising systems.

3.1.1 ALTERATIONS OF THE STANDARD STARCH SYSTEM

3.1.1.1 MODIFICATIONS OF THE STANDARD BRINE SUSPENDING MEDIUM

Two additions which would be expected to alter the dilatant properties are deflocculating agents and wetting agents. It has also been suggested[9] that changes in the pH could affect the dilatancy by altering the surface absorption characteristics of the particles. Each of these possibilities was evaluated. Tri sodium phosphate (TSP) was added to the brine solution as a wetting agent. However no changes in the impact properties of the suspension were observed. The effect of pH was evaluated by adding sodium hydroxide. Systems were tested at pH's of 4-5, 6, and 7. (The starch/brine has a pH of 3). The impact properties were unaffected. Gelatin and SPAN 20 (sorbitan monolaurate) were added to assess the effect of deflocculating agents. Specimens were impacted with additions of 1 and 3% Gelatin and 1 and 2% SPAN 20. The Gelatin had very little effect on the impact properties, but additions of SPAN 20 significently improved the properties. Two percent of this agent slightly increased the energy absorption efficiency and substantially decreased the peak deceleration. (The peak deceleration was over 20% less at an impact energy of 140 ft.lbs.) A final addition to the brine suspension was Cab-O-Sil. This is a thixotropic jelling agent composed of sub-micron sized silica particles. It should change the system's initial flow characteristics as well as impede any tendency for settling. However, it was found that although the Cab-O-Sil enhanced the impact properties of "fresh" suspensions it slightly increased the deceleration values of the suspension that had been allowed time to age (or settle). (See Table 5). The results of additions to the standard starch solution are summarized in Table 2. The properties of the standard solution are repeated in the table for ease of comparison.

TABLE 2: The Effect of Additives on the Impact Properties of the Standard Starch-Brine Suspension

Mix	E_I (ft·lbs)	V (ft/sec)	E_{abs} (%)	Pen. (in)	D Time (msec)	Peak Dec. (g)	Max. Jerk g/msec initial	final
#1 - Standard Starch Suspension	33.61	11.0	96.5	1.38	8.00	47.8	11.4	12.9
	58.77	11.0	95.4	1.53	8.30	45.7	10.6	11.3
	80.63	17.0	96.8	1.77	5.36	91.3	13.1	31.6
	140.98	17.0	97.3	1.84	7.30	83.7	15.6	31.6
#4 - Starch + TSP	33.61	11.0	96.3	1.40	7.25	48.0	7.82	11.4
	58.77	11.0	96.7	1.54	8.83	44.7	6.18	9.89
	80.63	17.0	97.6	1.73	6.83	87.0	14.3	30.0
	140.98	17.0	97.3	2.02	7.43	81.3	11.6	25.3
#2 - Starch pH 4-5	33.61	11.0	96.9	1.36	7.67	52.3	10.3	16.2
	58.77	11.0	96.1	1.47	8.40	50.0	9.13	13.8
	80.63	17.0	97.6	1.72	6.47	92.2	17.6	23.7
	140.98	17.0	97.3	1.95	7.40	85.7	19.1	25.0
#3 - Starch pH 6	33.61	11.0	96.8	1.28	8.03	48.0	8.56	15.6
	58.77	11.0	96.0	1.60	8.37	46.0	6.96	11.7
	80.63	17.0	96.8	1.77	6.57	88.7	17.1	26.6
	140.98	17.0	97.8	2.30	8.00	75.5	16.7	24.4
#6 - Starch pH 7	33.61	11.0	96.0	1.40	8.20	49.6	9.48	13.7
	58.77	11.0	96.5	1.43	8.56	46.0	8.70	11.6
	80.63	17.0	97.0	1.67	6.24	94.8	20.2	37.3
	140.98	17.0	97.5	1.93	7.10	88.6	13.9	26.6
#5 - Starch + 1% Gelatin	33.61	11.0	97.0	1.33	8.46	46.7	8.38	17.6
	58.77	11.0	97.0	1.56	8.53	47.0	6.43	14.7
	80.63	17.0	97.1	1.73	6.23	93.5	17.2	27.5
	140.98	17.0	97.9	1.96	7.33	86.3	11.9	27.3
#7 - Starch + 3% Gelatin	33.61	11.0	96.9	1.48	7.90	48.4	8.64	17.0
	58.77	11.0	96.8	1.60	8.30	47.7	7.23	12.2
	80.63	17.0	97.1	1.68	6.17	94.0	17.0	33.6
	140.98	17.0	97.2	1.87	6.70	95.7	17.8	24.2
#10-Starch + 1% SPAN 20	33.61	11.0	97.8	1.58	9.30	39.6	5.35	9.93
	58.77	11.0	98.6	1.92	10.4	37.2	4.38	9.78
	80.63	17.0	98.5	2.06	8.00	68.5	14.6	22.2
	140.98	17.0	98.9	2.33	8.26	68.0	12.9	20.6
#8 - Starch + 2% SPAN 20	33.61	11.0	97.9	1.58	8.26	35.0	6.60	9.85
	58.77	11.0	97.9	1.83	9.50	33.0	5.35	9.68
	80.63	17.0	98.5	2.00	7.57	63.0	14.4	21.4
	140.98	17.0	98.5	2.21	8.10	64.7	12.2	19.0
#13- Starch + 3% Cab-O-Sil	33.61	11.0	97.4	1.44	7.60	39.3	7.57	12.4
	58.77	11.0	97.9	1.81	8.90	35.3	5.76	11.9
	80.63	17.0	98.7	1.62	6.93	69.3	23.1	27.5
	140.98	17.0	99.1	2.14	7.73	63.6	13.2	21.3

3.1.1.2 CHANGES IN SUSPENDING MEDIUM FOR THE STARCH

The effect of changing the fluid medium was also evaluated for the starch system. The fluids used were methanol, ethylene glycol, and glycerine. Besides having lower freezing points than water, these fluids also inhibit biological decay of the starch. These fluids also vary in viscosity and lubricity for particles; methanol is lower than brine and ethylene glycol and glycerine are higher. The swelling potential for starch is greatest in brine. Systems with 44.5 vol.% starch suspended in each of these fluids were tested. A system of 44.5 vol.% starch in a 50/50 ethylene glycol/water solution was also tested since it has an extremely low freezing point. The results of these tests are summarized in Table 3. The starch-methanol system had very low peak deceleration and essentially 100% energy absorption efficiency. However its penetration was very large which could be a problem for very thin ejection seat cushions such as those to be used in the MEW seat. The starch-ethylene glycol system had nearly as good impact properties as the standard starch + 2% SPAN 20 system. (The energy absorption efficiency was higher for the former, however, the peak deceleration values were not as good). The starch-glycerine suspension was found to be unacceptable as a cushion material because of its excessive penetration when fresh and because it became very hard upon standing. The hardening is likely due to a chemical reaction of the type which occurs in adhesive paste cements. The starch in 50/50 ethylene elycol/water system had impact properties very similar to the standard starch suspension. It would be an excellent system for low temperature applications.

3.1.1.3 OPEN PORE FOAM ADDITIONS TO STARCH/BRINE

A property of dilatant suspensions which is desirable in cushion materials is its tendency for continued flow under constant pressure at low velocity. This property permits conformity to the pilot's body, but some control is required. One method is to thixotropically gel the suspending fluid such that it will remain immobile under static forces but will flow and become

TABLE 3: The Effect of Changing the Fluid Medium on the Impact Properties of Starch Dilatant Suspensions

Mix	E_I (ft·lbs)	V (ft/sec)	E_{abs} (%)	Pen. (in.)	D Time (msec)	Peak Dec.(g)	Max. Jerk (g/msec) Initial	Final
#1-Standard	33.61	11.0	96.5	1.38	8.00	47.8	11.4	12.9
Starch	58.77	11.0	95.4	1.53	8.30	45.7	10.6	11.3
Suspension	80.63	17.0	96.8	1.77	5.36	91.3	13.1	31.6
	140.98	17.0	97.3	1.84	7.30	83.7	15.6	31.6
#9-Starch	33.61	11.0	100.0	2.30	10.6	30.5	3.94	14.0
in	58.77	11.0	99.9	2.53	10.9	36.8	4.17	12.3
Methanol	80.63	17.0	100.0	2.70	9.33	52.5	11.2	25.6
(44.5 vol %)	140.98	17.0	100.0	3.00	8.73	64.2	11.9	21.2
#14-Starch in	33.61	11.0	99.0	1.46	6.53	45.0	5.76	19.3
Ethylene	58.77	11.0	98.8	1.62	7.76	42.0	4.74	19.1
Glycol	80.63	17.0	99.5	1.77	6.20	70.7	13.6	39.1
(44.5 vol.%)	140.98	17.0	99.2	2.10	7.03	69.7	8.65	40.8
#16-Starch in	33.61	11.0	99.9	2.85	17.0	17.3	1.74	2.79
Glycerine	58.77	11.0	99.9	3.00	12.5	21.7	2.01	4.30
(44.5 vol.%)	80.63	17.0	100.0	3.12	9.43	43.3	4.41	10.1
	140.98	17.0	99.9	3.12	5.53	65.3	11.6	21.8
#12-Starch in	33.61	11.0	98.2	1.37	7.33	46.7	9.18	15.2
50/50	58.77	11.0	97.9	1.47	8.40	47.8	7.91	13.2
Ethylene	80.63	17.0	98.2	1.63	6.57	90.8	20.4	35.6
glycol/H_2O	140.98	17.0	98.4	1.80	7.05	82.4	17.6	28.2

TABLE 4: The Effect of Infiltration into Open Cell Foam on the Impact Properties of the Standard Starch Brine Suspension

Mix	E_I (ft·lbs)	V (ft/sec)	E_{abs} (%)	Pen. (in.)	D Time (msec)	Peak Dec.(g)	Max. Jerk (g/msec) Initial	Final
#1-Standard	33.61	11.0	96.5	1.38	8.00	47.8	11.4	12.9
Starch	58.77	11.0	95.4	1.53	8.30	45.7	10.6	11.3
Suspension	80.63	17.0	96.8	1.77	5.36	91.3	13.1	31.6

dilatant, when the critical shear stress is exceeded. A second method to counteract this, is to use dilatant suspensions which are infiltrated into low volume, open cell reticulated foams. Impact tests were run to determine whether the foam altered the dilatant properties. The standard starch suspension was infiltrated into three different polyurethane foams manufactured by the Scott Paper Company. Care was taken to remove all air. The foams had pore sizes of 10, 20, and 40 pores per inch. The results are summarized in Table 4. As the table shows infiltrating the suspension into the foams significantly decreases the peak deceleration and slightly increases the energy absorption efficiency. The pore size of the foams appears to have little effect on the impact properties.

3.1.1.4 STORAGE STABILITY

The starch-brine dilatant suspension has a tendency to "stiffen" somewhat when it is allowed to "settle" for an extended period of time. To determine whether this has any effect on the energy absorbing properties, impact tests were run on several specimens that had settled for over two months. The results are reported in Table 5. In general, the specimens showed a decrease in penetration. This was expected since the settled suspensions were stiffer and more dense. However, they also showed decreased peak deceleration values. A noteable expection was the suspension containing Cab-O-Sil, as mentioned previously. Bacteriological decay was considered as a possible cause for this effect, however, examination of the suspensions indicated that no decay had occurred in the presence of the brine. Swelling of the individual starch particles was also suspected, but examination under the optical microscope eliminated the possibility of gross swelling. Air bubble degassing could also have occurred (and would not with Cab-O-Sil gelled material). To determine whether the effect was due to a time-dependent, intrinsic change in the systems or simply due to the physical settling, selected specimens were re-tested after thorough kneading. The results are shown in Table 6. As the table shows, the

TABLE 5: The Effect of Settling on the Impact Properties of Various Starch Brine Suspensions

Mix	E_I (ft·lbs)	V (ft/sec)	E_{abs} (%)	Pen. (in.)	Dwell Time (msec)	Dec. (g)	Max. Jerk (g/mil-sec) Initial	Final
#2-Starch pH 4-5	33.61	11.0	96.9	1.36	7.67	52.3	10.3	16.2
	58.77	11.0	96.1	1.47	8.40	50.0	9.13	13.8
	80.63	17.0	97.6	1.72	6.47	92.2	17.6	23.7
	140.98	17.0	97.3	1.95	7.40	85.7	19.1	25.0
#2-Starch "Settled"	33.61	11.0	95.7	1.25	8.0	43.0	10.3	11.4
	58.77	11.0	96.8	1.30	8.6	44.0	9.53	11.4
	80.63	17.0	97.2	1.70	7.0	70.0	18.2	22.2
	140.98	17.0	97.4	1.95	7.5	69.0	18.2	21.0
#3-Starch pH 6	33.61	11.0	96.8	1.28	8.03	48.0	8.56	15.6
	58.77	11.0	96.0	1.60	8.37	46.0	6.96	11.7
	80.63	17.0	96.8	1.77	6.57	88.7	17.1	26.6
	140.98	17.0	97.8	2.30	8.00	75.5	16.7	24.4
#3-Starch pH 6 "Settled"	33.61	11.0	95.8	1.35	8.2	42.0	6.78	10.5
	58.77	11.0	96.4	1.30	9.0	38.0	6.35	10.0
	80.63	17.0	97.4	1.70	7.5	67.0	12.5	22.2
	140.98	17.0	97.7	2.00	7.5	68.0	12.9	22.2
#6-Starch pH 7	33.61	11.0	96.0	1.40	8.20	49.6	9.48	13.7
	58.77	11.0	96.5	1.43	8.56	46.0	8.70	11.6
	80.63	17.0	97.0	1.67	6.24	94.8	20.2	37.3
	140.98	17.0	97.5	1.93	7.10	88.6	13.9	26.6
#6-Starch pH 7 "Settled"	33.61	11.0	96.6	1.25	8.8	42.0	10.0	11.4
	58.77	11.0	97.9	1.60	10.0	36.0	5.90	9.30
	80.63	17.0	98.0	1.50	7.2	74.0	11.8	26.6
	140.78	17.0	98.6	1.95	8.0	68.0	8.34	25.0
#10-Starch 1% SPAN 20	33.61	11.0	97.8	1.58	9.30	39.6	5.35	9.93
	58.77	11.0	98.6	1.92	10.4	37.2	4.38	9.78
	80.63	17.0	98.5	2.06	8.00	68.5	14.6	22.2
	140.98	17.0	98.9	2.33	8.26	68.0	12.9	20.6
#10-Starch 1% SPAN "Settled"	33.61	11.0	97.4	1.50	10.2	32.0	5.72	8.90
	58.77	11.0	96.9	1.55	10.0	35.0	4.22	8.34
	80.63	17.0	98.6	1.82	10.0	50.0	8.90	14.3
	140.98	17.0	98.2	2.10	8.2	62.0	9.53	19.0
#13-Starch 3% Cab-O-Sil	33.61	11.0	97.4	1.44	7.60	39.3	7.57	12.4
	58.77	11.0	97.9	1.81	8.90	35.3	5.76	11.9
	80.63	17.0	98.7	1.62	6.93	69.3	23.1	27.5
	140.98	17.0	99.1	2.14	7.73	63.6	13.2	21.3
#13-Starch Cab-O-Sil "Settled"	33.61	11.0	97.7	1.41	7.73	41.0	9.01	13.9
	58.77	11.0	98.2	1.49	7.76	44.0	6.37	14.9
	80.63	17.0	97.1	1.70	6.56	75.0	18.1	23.6
	140.98	17.0	98.6	1.96	6.86	75.0	13.5	24.6

TABLE 6: The Effect of Kneading on the Impact Properties of "Settled" Starch Brine Suspensions

Mix	E_I (ft·lbs)	V (ft/sec)	E_{abs} (%)	Pen. (in.)	Dwell Time (msec)	Peak Dec. (g)	Max. Jerk (g/msec) Initial	Final
#2-Starch pH 4-5	33.61	11.0	96.9	1.33	7.35	42.5	7.34	11.9
	58.77	11.0	96.9	1.58	8.30	42.0	8.17	11.1
	80.63	17.0	97.7	1.65	6.24	77.0	21.6	26.6
	140.98	17.0	97.9	1.97	7.27	70.0	17.9	23.3
#3-Starch pH 6	33.61	11.0	97.2	1.27	8.36	41.3	6.99	10.8
	58.77	11.0	97.9	1.60	9.70	38.0	6.25	9.83
	80.63	17.0	98.1	1.83	7.15	68.0	13.6	21.6
	140.98	17.0	98.3	2.04	8.25	61.3	11.4	20.5
#10-Starch + 1% SPAN 20	33.61	11.0	97.4	1.58	9.10	36.3	7.50	9.13
	58.77	11.0	97.9	1.86	9.50	35.3	5.17	8.90
	80.63	17.0	98.0	2.00	7.80	65.5	13.4	21.6
	140.98	17.0	98.0	2.38	8.00	63.0	9.88	19.5

peak deceleration values remained lower than those of fresh mixes. This indicates that the improved values are the result of an intrinsic "aging" process. The likely explanation is that progressive wetting occurs during aging which causes the particles to become more completely deflocculated. Reference to Tables 5 and 6 also shows that energy absorption efficiency remains high regardless of the testing conditions. These results demonstrate that the excellent impact properties of the dilatant suspensions are not degraded but in fact improve with time.

3.1.1.5 STARCH PARTICLE SIZE EFFECTS

The effect of particle size was also evaluated for the starch-brine system. This was done by separating the starch into three different particle size ranges (75 - 124 μ, 45 - 74 μ, and < 44 μ) using standard mesh sieves. Brine suspensions of each of the size ranges were made and tested qualitatively. Rheological dilatancy - as determined by increasing resistance to flow with increasing shear rate - was observed for all three particle size ranges. No significant differences between the different sizes was observed. Volume dilatancy - as determined by drying of the surface of the suspensions during shearing - was also observed in all three cases. However, it was much more pronounced in the smaller particle size suspension (< 44 μ) than in the two suspensions with larger particles.

3.1.2 EVALUATION OF OTHER DILATANT SYSTEMS

The dilatant properties of numerous other systems were evaluated. We were seeking systems of different impact behavior as well as systems of different density. The procedure was to qualitatively test the suspension for dilatancy and then impact the most promising systems. Many of the systems tested exhibited no dilatant behavior, although the technical literature indicates dilatancy to be not infrequent, achieving it requires very careful

selection of particle size, size distribution, shape, surface characteristics, and porosity. Table 7 lists the systems which were surveyed by mixing (with and without wetting agents) and screening for dilatancy (i.e., flow stiffening as shear is increased). As the table shows, the systems of oxides in water, graphite and carbon black in oil, and candy sprinkles in alcohol were not dilatant. One system of graphite (28.4 vol.%) and silicone oil was impacted at the lowest energy level (33.61 ft.lbs) and it was evident that the mix offered little resistance to the pendulum, penetration being almost complete.

Another system which was evaluated was a suspension of hollow glass beads in water. These were obtained from Emerson and Cuming Inc. Three different grades were tested: IG 101, FTD 200 and $ with particle sizes 10 - 250 μ, 10 - 100 μ (90%) and 30 - 200 μ respectively. All three showed pronounced dilatant behavior when mixed with water. The jelling agent, Cab-O-Sil, was added to the IG 101 and the FTD 200 mixes. The Cab-O-Sil was found to produce initial pseudoplasticity in the 101 mix and it was not added to the mixes used for impact testing. A suspension of type R Eccospheres (59 vol.%) in water was impacted. The results are shown in Table 8. The mix produced very low peak deceleration but very high penetration. Subsequent microscopic examination of the impacted particles showed that they had been crushed by the impact. Therefore further testing of the hollow glass beads was not conducted. However, since the glass beads constituted a strongly dilatant material with different response characteristics from the starch-brine suspension, tests were continued with solid glass microbeads.

Spherical, solid glass microbeads were obtained from the 3M Co. Suspensions of microbeads and water were evaluated for 29, 38 and 50 μ particle sizes. A 61.6 vol.% suspension of the 29 μ beads was impact tested. The results (Table 8 were quite striking. This system produced the lowest rebound angle and thus the highest energy absorption efficiency of all the systems tested. It also produced the lowest peak deceleration values. However, the exact value of the peak deceleration could not be measured at the high impact energies due to a "ringing effect". (The values in Table 8 are averages). This is illustrated in Figure 3 which shows the deceleration trace for the glass bead suspension at an impact energy of 80.63 ft.lbs. The cause of this "ringing cannot be determined with the

Name	Suspended Particulate: Source/Description	Size (u)	Shape	Density (g/ml)	Fluid Medium	Remarks
Iron Oxide	Citgo-Mapico Yellow 1000	0.1-0.8	Acicular	4.05	Water	Not dilatant
	Citgo-Mapico Yellow 2150	0.1-0.8	Acicular	4.06	Water	Different absorption characteristics from Mapico Yellow 1000 - not dilatant
	Citgo-Mapico Roasted Copperas Red 297	0.3-0.8	Spherical	5.18	Water	Not dilatant
	Citgo-Mapico Pure Synthetic Brown 420	0.2-0.4	Cubical	4.69	Water	Not dilatant
TiO_2	Reagent Grade	1.0-5.0		4.26	Water	Not dilatant
Graphite	Std Lab Grade	74	Flake		Silicone Oil	Thixotropic
Carbon Blk	Citgo-Raven 150	.018		0.27	Silicone Oil	Thixotropic
	Citgo-Royal Spectra	.010		0.09	Silicone Oil	Thixotropic
Candy (Sprinkles)	Beaver Home Prod., Inc.	1-2 mm	Spheres	∿1	Alcohol	Not Dilatant
Hollow Glass Spheres	Emerson & Cuming "Eccospheres" IG 101	10-250	Spherical	0.22	Water with/ without Cab-O-Sil	Dilatant with water only, Cab-O-Sil produced pseudoplasticity
	Emerson & Cuming "Eccospheres" FTD 200	10-100	Spherical	0.28	Water with/ without Cab-O-Sil	Dilatant with water only, Cab-O-Sil produced pseudoplasticity
	Emerson & Cuming "Eccospheres" R	30-200	Spherical	0.24	Water	Dilatant
Solid Glass Beads	3M-"Scotchbrite"	29	Spherical	1.5	Water	Dilatant
	3M-"Scotchbrite"	38	Spherical	1.5	Water	Dilatant
	3M-"Scotchbrite"	50	Spherical	1.5	Water	Dilatant
Silica Flour	Ottawa Silica-Silica Flour	105	Angular	∿1.4	Water	Dilatant

TABLE 8: Impact Properties of New Dilatant Systems

Mix	E_I (ft·lbs)	V (ft/sec)	E_{abs} (%)	Pen. (in.)	Dwell Time (msec)	Peak Dec. (g)	Max. Jerk (g/msec) Initial	Max. Jerk (g/msec) Final
#17-Hollow Glass Beads	33.61 58.77 80.63	11.0 11.0 17.0	97.9	3.20	12.8	23.6	2.34	7.65

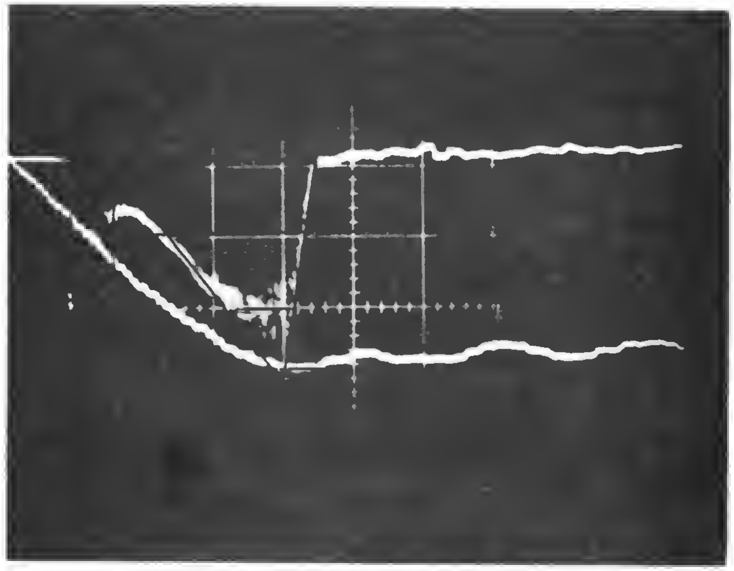


Fig. 3. Oscillograph of Deceleration and Penetration for a 61.6 vol. % Suspension of Glass Microbeads (29μ) in Water. Initial Impact Energy was 80.63 ft·lbs.

available information.

The final system which was impacted consisted of a suspension of 78.5% silica flour in water. The silica flour, 140 mesh (105 μ) with an angular shape, was obtained from the Ottawa Silica Corp. This system showed definite dilatancy and was therefore impact tested. The results are shown in Table 8. It can be seen that its impact properties are better than the standard starch suspension (see Table 1) but not as good as the starch + 2% SPAN or the glass microbeads.

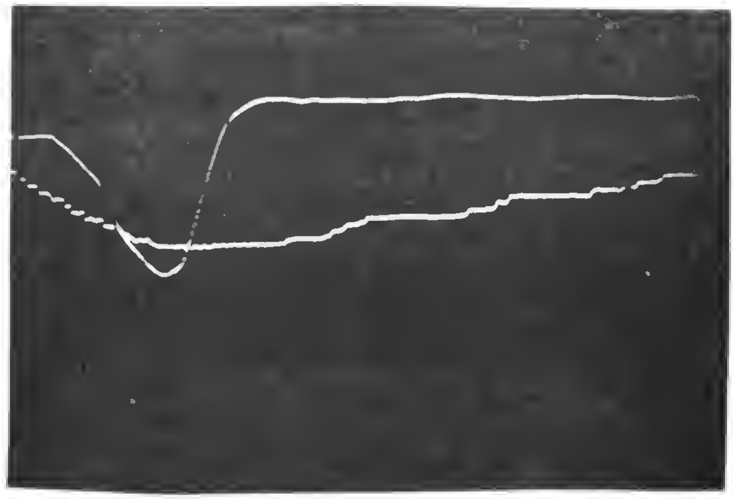
The lycopodium system showed definite dilatancy but was discovered too late in the program to be impacted.

Although extensive searching took place through plastic manufacturers, no source of plastic microspheres was found other than the very very expensive Dow material used for electron microscopy calibrations. We feel, however, that such microspheres could be made inexpensively from polyethylene and would be inherently biologically stable but of the same low density as starch powder.

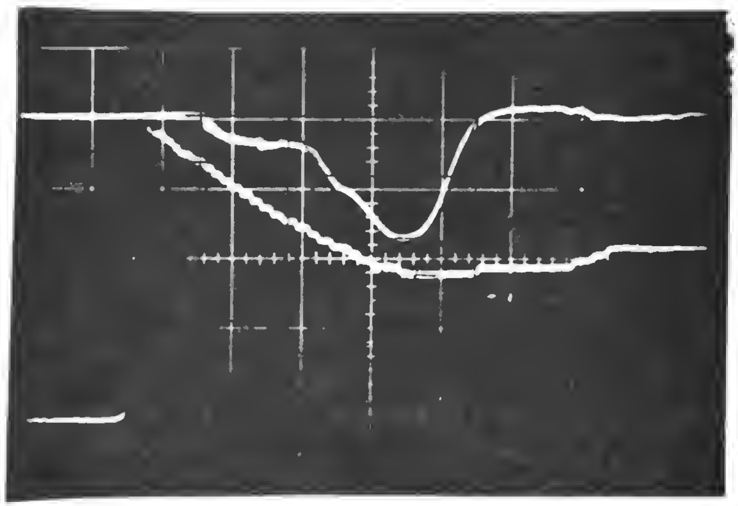
3.1.3 SUMMARY

This phase of the research program has resulted in the development of two dilatant systems which show superior impact properties. They are (1) 50% starch + 2% SPAN 20 in a concentrated (26.5%) NaCl solution and (2) 80.5% glass microbeads (29 μ) in water. The superior properties of these two systems is illustrated in Figure 4, which shows deceleration traces for specimens impacted at an energy of 33.61 ft. lbs. Figure 4(a) shows the trace for the standard starch-brine which is in itself, an excellent impact energy absorber. However, the improved properties of the starch + SPAN 20, Figure 4(b), and the glass microbeads, Figure 4(c), are quite obvious. The glass microbead suspension is of interest not only because of its excellent impact energy absorption but also because it represents a system with different dilatant properties (compare the shapes of the Figures 4(b) and 4(c)) than the starch suspensions.

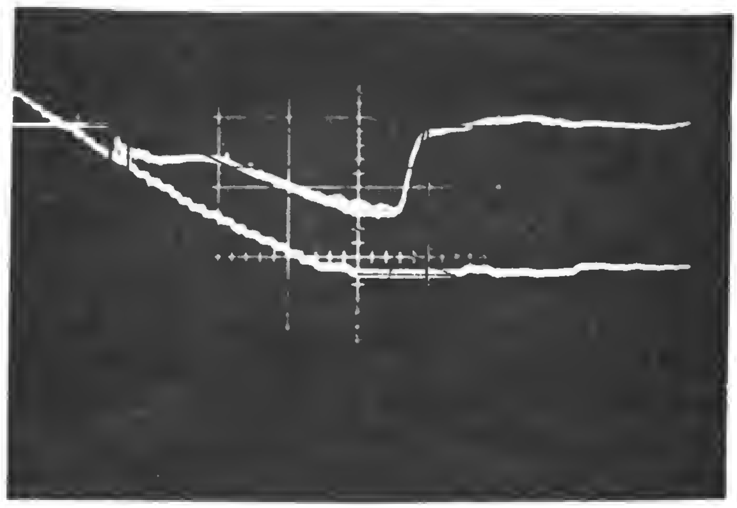
Table 9 is a summary comparison of the properties of a number of the dilatant systems which were evaluated in this investigation. The suspensions



(a) Standard 50% Starch-Brine Suspension;



(b) Standard 50% Starch-Brine Suspension with 2% SPAN 20,



(c) Suspension of 61.6 vol. % Glass Microbeads (29μ) in Water.

Fig. 4. Comparison of Deceleration and Penetration Curves during Impacting with an Initial Impact Energy of 33.61 ft·lbs :

ase ystem	Variables		Energy Absorp. Efficiency	Peak Deceleration	Penetration	Remarks
tarch	Standard Brine	-	Standard	Standard	Standard	
	Brine + TSP	Wetting Agent	Unchanged	Unchanged	Unchanged	
	Brine + NaOH	pH Alteration	Unchanged	Unchanged	Unchanged	
	Brine + Gelatin	Defloc. Agent	Unchanged	Unchanged	Unchanged	
	Brine + SPAN 20	Defloc. Agent	Better	Better	Slightly worse	Best system tested
	Brine + Cab-O-Sil	Dilatant Suspension in a thixotropic fluid	Better	Better	Slightly worse	
	Methanol	Low freez. point, low viscosity fluid	Better	Better	Much worse	
	Ethylene Glycol	Low freez. pt., high viscosity fluid	Better	Better	Slightly worse	
	50/50 Ethyllene glycol/ H_2O	Very low freezing pt, intermediate viscosity fluid	Unchanged	Unchanged	Unchanged	
	St'd brine infiltrated into open cell foam	Retards settling	Better	Better	Unchanged	
ollow Glass Beads Microspheres)	Water		etter	Better	Much worse	Beads crushed during impact
olid Glass Beads Microspheres)	Water		BBetter	Better	Worse	Highest energy absorption efficiency & lowest peak dec. of all sys. tested. Produces ringing effect a high impact energies
ilica Flour	Water		Better	Better	Worse	
ycopodium		Lycopodium is a pollen of low density similar to starch	Discovered too late to impact.			

TABLE 9: Comparison of the Properties of Dilatant Systems

are rated as to their performance compared to the standard starch-brine system. All of these systems have excellent impact absorption characteristics when compared to non-dilatant materials. It should also be pointed out that although many additions to the starch-brine suspension did not alter the impact properties they may still have altered the low shear rate behavior, but it was not noticed at the very high shear rates of the impact test.

3.2 COMPARISON OF DILATANT MATERIALS TO CURRENTLY USED IMPACT ABSORBING MATERIALS

Numerous impact absorbing materials were obtained and tested in the modified impact tester in order to compare them directly with the dilatant materials. Tests were run on three different foam materials and one aluminum honeycomb material. The results are shown in Table 10 in order of improving properties, the worst performer listed first. As the table shows Bendix Corporation's M.D. cushion (used in the early F-4 aircraft) had the worst properties. This cushion was constructed from two different foam materials, one in the center and one on the outside. Both materials had very poor impact energy absorbing properties. The P-60 foam (an open cell polyurethane type produced by the General Tire Co.) had slightly better properties at low impact energies, however, it could not be tested at high energies due to the very large penetration. The third foam material tested was made by Frost Engineering. It had impact properties significantly better than the other foam materials. The Al honeycomb material absorbs energy by being crushed. Therefore, in order to evaluate its impact properties the area of the specimens was controlled so that the honeycomb would be completely crushed at each impact energy. As the table shows, this material had very good energy absorption efficiency but very high peak deceleration. The starch + 2% SPAN 20 dilatant material is listed at the bottom of the table for comparison. Its superior impact absorption properties are obvious. The best foam material (Frost Engineering foam) has comparable properties at low impact energies but is clearly inferior at high impact energies. The Al honeycomb structure has comparable energy absorption efficiency but much larger peak deceleration at the high impact energies.

TABLE 10 - Comparison of Various Impact Absorbing Materials

Material	E_I (ft·lbs)	V ft/sec	E_{abs} (%)	Pen. (in.)	Dwell Time (msec)	Peak Dec. (g)	Max. Jerk (g/msec) Initial	Final
M.D.Cushion (2" thick) Center	33.61	11.0	65.8	1.0	8.5	78.4	20.1	10.8
	58.77	11.0	68.6	1.1	10.5	59.9	11.8	8.45
	80.63	17.0	78.3	1.28	7.85	128.5	25.8	21.2
M.D. Cushion (2" thick) Outside	33.61	11.0	66.4	1.0	7.9	88.7	19.7	14.3
	58.77	11.0	70.1	1.08	11.0	59.3	9.09	7.58
	80.63	17.0	77.4	1.35	8.0	115.2	26.9	21.2
P-60 Foam (4" thick)	33.61	11.0	88.2	3.68	5.50	58	10.5	18.5
	58.77	11.0	87.3	3.96	3.93	91	23.1	23.9
Frost Eng. Foam (2" thick)	33.61	11.0	95.3	1.35	16.0	29.0	9.23	3.14
	58.77	11.0	91.9	1.46	12.8	32.3	4.38	4.73
	80.63	17.0	85.2	1.75	6.56	80.0	12.1	24.1
	140.98	17.0	65.4	1.98	3.70	120.0	33.4	40.0
Al Honeycomb (1.5" thick)								
1.0" x 1.0"	58.77	11.0	99.5	~1.40	3.0	68	~9.76	40.0
1.25" x 1.25"	80.63	17.0	99.8	~1.40	2.0	130.0	~10.5	21.0
1.5" x 1.5"	140.98	17.0	98.8	~1.40	2.3	130.0	~20.0	40.0
Starch + 2% SPAN 20	33.61	11.0	97.9	1.58	8.26	35.0	6.60	9.85
	58.77	11.0	97.9	1.83	9.50	33.0	5.35	9.68
	80.63	17.0	98.5	2.00	7.57	63.0	14.4	21.4
	140.98	17.0	98.5	2.21	8.10	64.7	12.2	19.0

3.3 COMPARISON OF THE FIRL IMPACT TEST TO SIMULATED EJECTION TEST.

Information[10] from simulated ejection tests indicated that the M.D. (Bendix) cushion was a very poor performer and that the P-60 foam was measureably better. These results correlate well with the FIRL tests in which the M.D. cushion was clearly inferior to the P-60 foam (see Table 10). This comparison could be made more quantitative if the Martin Baker (M.B.) cushion had been available to give a third point on the correlation. However, the superiority of the dilatant suspensions over both the foam materials is clearly strong evidence that dilatant systems would make excellent ejection seat cushions.

4. CONCLUSIONS

1) Two dilatant systems have been found to exhibit superior impact properties. They are (1) 50% starch + 2% SPAN 20 in a concentrated (26.5%) NaCl solution and (2) 80.5% glass microbeads (29 μ) in water.

2) The impact absorbing properties of the dilatant suspensions were found to be clearly superior to other currently used energy absorbing materials.

3) The impact parameters measured in the FIRL tests were qualitatively found to correlate with the forces experienced during simulated ejection tests.

5. REFERENCES

1. *Biodynamic Response of the Human Body,* Von Gierke, H. E., Appld. Mechs. Rev., V. 17, No. 12, Dec. 1964, 173.

2. *Response of the Seated Human Cadaver to Acceleration and Jerk with and without Seat Cushions,* Hum. Factors 5, Oct. '63, 505-2.

3. *Biomechanical Analysis of Knee Impact",* Cooke, F. W., Nagel, D. A., 13th Stapp Car Crash Conf. Boston, Mass. Dec. 2-4, 1969. (Publisher, S.A.E., 2 Penn Plaza, N.Y.C.).

4. *Development of Aerospace Escape Systems",* Brinkley, J. W. Air Univ. Review, Jul-Aug. 1968. 74.

5. *Properties of Liquids,* Wohl, M. H., Chemical Engineering, Apr 14, 1968, 11.

6. Cooke, F. W., Rosenberg, B. L., and Kelly, M.G., *Experimental Systems for Impact Protection,* FIRL Report No. NADC-AC-7003, April 16, 1970.

7. *Flow Behavior of Concentrated (Dilatant) Suspensions,* Metzner, A. B. and Whitlock, M., Trans. Soc. Rheol. 11, 1958, 219.

8. *Thixotropy and Dilatancy,* Bauer, W. H., Collins, E. A., Rheology: Theory and Applications, Vol. IV, F. R. Eirich ed., Academic Press, N. Y. and London, 1967.

9. Morgan, R. J., Trans. Soc. Rhoelogy 12, 511 (1968).

10. Private Communication, Brinkley, J. W., Aerospace Medical Research Laboratory, Wright Patterson AFB, Feb., 1970.

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13. ABSTRACT

The energy absorption characteristics of a number of dilatant suspension systems were evaluated using a modified pendulum impact tester. Two systems which were found to have superior impact energy absorption properties are 50% corn starch + 2% SPAN 20 in a concentrated (26.5%) NaCl solution and 70.5% glass microbeads (29) in water. The impact properties of all the dilatant systems were found to be significantly better than currently available ejection seat cushion materials. A qualitative correlation between the impact parameters measured in this investigation and the forces experienced during simulated ejection tests was made.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Dilatant Materials						
Energy Absorption						
Seat Cushions						
Impact						
Acceleration						